Comparing the Economic Impact of Alternative Metrology Methods in Semiconductor Manufacturing

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***Abstract*—Metrology is an essential part of advanced semiconductor manufacturing. It accelerates yield improvement and sustains yield performance at every stage in both new and mature processes. Advances in metrology are needed to achieve challenging industry goals, such as smaller feature sizes and reduced time for introduction of new materials and processes for future technology. To achieve difficult industry goals, it is expected that metrology practices will migrate from offline to inline, and ultimately, to *in situ*. Economic models are needed to study the costs and benefits of introducing new metrology technologies and to compare alternative metrology practices. Several qualitative and quantitative models are presented in this paper to study the elements of revenue and cost associated with different metrology tools and practices. Comparisons between *in situ*, inline and offline metrology systems are made. The cost components of the metrology methods are analyzed and discussed with respect to steady state process control as well as their effect on time to yield. Monte Carlo simulation models are used to study each system under different scenarios.**

***Index Terms*—Continuous-time Markov chain, economics, metrology, semiconductor manufacturing.**

I. INTRODUCTION

HISTORICALLY, semiconductor manufacturers rely on statistical process control (SPC) techniques for maintaining the processes within prescribed specification limits. While semiconductor manufacturing has continued to pursue ever-tightening specifications due to the well-known problems associated with the decreasing feature size, it has also become clear that there is a need for advanced-integrated process control. This approach requires a major shift in operational methods and requires the existence of complex, flexible architectures to meet the above requirements. New metrology tools are introduced as an essential part of these architectures.

Metrology accelerates yield improvement at every stage in both new and mature processes. Appropriate metrology practices can reduce the cost and cycle-time of manufacturing through better characterization of tools and processes. Advances in metrology are needed to achieve difficult industry goals, such as smaller feature sizes and reduced time for introduction of new materials and processes for future technology. To achieve these goals, it is expected that metrology practices will migrate from offline to inline, and ultimately be integrated in the tools ("*in situ*") [1].

Researchers have concentrated on the economic impact of particular aspects of metrology tools such as the sampling policy [2], [3] and the precision [4]. Dance *et al.* [5] tried to capture the economic behavior of metrology tools through a modified cost of ownership (COO) model. Still there is a need for more comprehensive models to identify elements of cost in complex metrology systems.

Unless convinced otherwise, manufacturers are usually reluctant to adopt major equipment and technology changes because of the short-term uncertainties that arise during the introduction of new technologies. Appropriate metrology models assist the semiconductor manufacturers to assess the costs that drive their businesses and help them in formulating the right operational strategies. The ability to effectively identify cost drivers and manage cost reductions is a competitive advantage for any manufacturer. Therefore, accurate models are needed to study the costs and benefits of introducing new technologies and evaluate different practices. Toward this goal, this paper introduces new analytical models to compare different metrology methods in a litho track system.

Although this study tries to address the economics of metrology systems in a general form, the examples and illustrations are developed for litho track systems. Lithography steps are among the most crucial, and lithography tools are among the most expensive in semiconductor manufacturing. Most of the models offered in this document can easily be modified and extended to other equipment sets and metrology tools.

Fig. 1 shows different metrology methods in a litho track system in terms of the position of the metrology tool in the system. Wafers first enter the track system, where they go through steps such as coating and baking in preparation for the main lithography process (stepper), in which small features are printed on the wafer. After lithography, wafers go through additional steps in the track system, such as post exposure bake (PEB) and development (DE).

The qualities of the features defined during lithography (which in turn depends on the quality of the lithography process) have a direct effect on the quality of the final product. Therefore, we are interested in measuring and controlling the quality of the lithography step. The quality of the process (here the lithography step) is represented by measuring certain quantities on the wafer, such as the critical dimension (CD) of fine printed patterns.

Offline systems, as depicted in Fig. 1(a), have traditionally been practiced by semiconductor manufacturers. In this method,

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Manuscript received May 9, 2002; revised July 15, 2002.

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Digital Object Identifier 10.1109/TSM.2002.804909

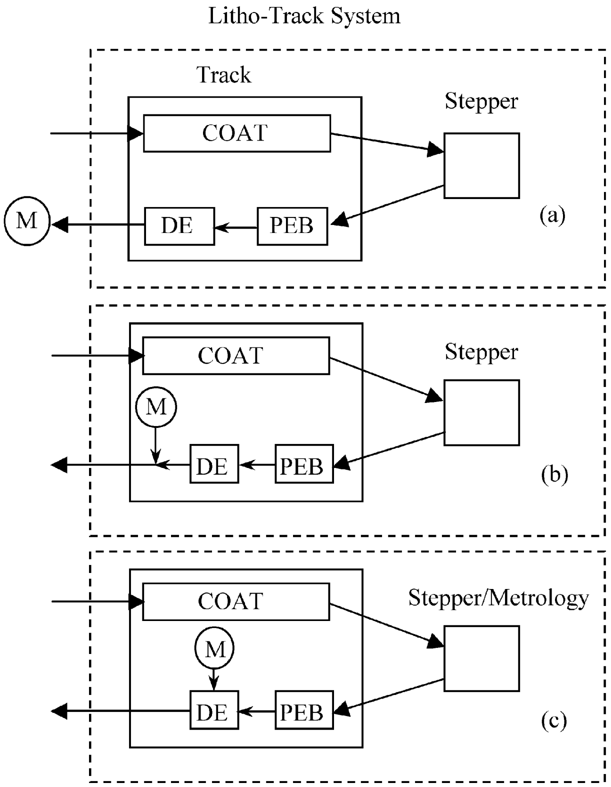

Fig. 1. Different metrology methods applied to a Litho track system: (a) offline, (b) inline, and (c) *in situ*. "M" indicates the position of the metrology tool.

the metrology tool is located after the track system. Wafers are transported to the metrology tool by lots. Lots are then measured by the metrology tool with an appropriate sampling policy. Offline metrology tools are usually accurate and fast, but are also expensive and occupy significant clean room space.

Newer inline systems occupy little footprint in the fab. Their accuracy and speed, however, is generally inferior to offline, though rapidly improving. *In situ* metrology systems are fully integrated and the measurements are done while the wafers are being processed or shortly after the process is completed. *In situ* lithography systems are under development and expected to be introduced with future generations of lithography tools.

To study the elements of cost in the above system, several qualitative and quantitative models are introduced in this paper. In the next section, the major components of the costs and benefits for metrology practices are analyzed and two revenue and cost models are introduced. The effects of metrology methods on revenue during the steady state and the time to maturity are explained. Monte Carlo simulation studies are conducted to compare different scenarios in Section III. First, the results of analytical model are compared to those of simulation model for a simple system. Then, the effects of yield and price structure, control policies, and the precision of metrology tools are examined in a series of scenarios. The results are presented and analyzed for each scenario. Recommendations are provided for each scenario and results are discussed. Conclusions and future avenues of study are explored at the end. flows in our models, or attempt to evaluate the investments in terms of interest rates or discounted returns or tax benefits.

II. Analytical Models of Metrology Methods

In general, since metrology operations are in series with the processes, they reduce the throughput and increase the work in process (WIP) and the cycle time. WIP inventory between a process step and the subsequent inspection is at risk if the process drifts to an undesirable state. Manufacturers have been trying to reduce these risks using different methods such as changing the sampling policies and send-ahead samples.

Simply reducing the number of samples may result in a better cycle time and WIP, but it negatively affects the throughput of good products. Product yields at subsequent steps depend on the quality of information extracted from the metrology data. The quality of information generated from the metrology measurements can be partly characterized by its accuracy, precision and sampling policy.

It is desirable to identify bad products passing through the metrology tool and detect the out of control state of the process as soon as possible. This can be achieved by tightening the acceptance criteria. If, however, these criteria are too tight, then good products may be rejected, or the system may be shut down unnecessarily, resulting in production loss.

Another cause for production loss is the WIP between the process tool and the metrology tool. If the process drifts to an undesirable state, the process keeps manufacturing bad products until they are detected by the metrology tool. All the product in WIP processed since the process went out-of-control needs to be reworked or discarded. A send-ahead (also known as look-ahead) sample method eliminates the WIP risk but reduces the process throughput and utilization. In the send-ahead sampling method, one or more wafers are processed and then submitted for measurement. The remaining wafers in the batch are processed after the measurements are complete, the results are released and the equipment is adjusted.

Therefore, it is also desirable to minimize the WIP in the system. Assuming the same throughput for metrology tools, migrating from offline to inline and *in situ* usually reduces the WIP. In other words, integrated inline and *in situ* metrology operation minimizes the WIP lost with little impact on utilization. However, the feasibility of these approaches and the quality of data collected by inline and *in situ* tools, along with the price tag of these types of equipment, should be considered in making a decision.

A. Overall Equipment Efficiency (OEE)

Overall equipment efficiency (OEE) is one of the most important metrics for measuring equipment performance. OEE is defined as the ratio of the theoretical time needed to produce salable wafers in a given period, divided by the total time in that period [7]. Theoretical time refers to the time required by a machine in perfect working order performing the process specification under ideal conditions.

Since, in this study, we are mainly interested in understanding

The first set of losses is associated with the metrology tool, its specifications, and the control policy chosen to detect and improve the bad process. The term "Bad process," in this document, refers to the process that is out of control and produces out-of-spec products; the products that are not conforming to the required specifications set by the fab management. These specifications are those that are measured by the metrology tool. The crosshatched area between OEE and OEE* in Fig. 2 shows the first set of losses. These losses are the focus of this study and will be further explored.

The second set of losses contains any loss that is not captured in the first set. These losses are those that occur regardless of the type of metrology tool and the control policy. Any loss of production due to unavailability of machine, bad utilization of equipment and slow process belongs to this category. The area between the OEE and 100% available time in Fig. 2 shows this set of losses.

B. A Mathematical Model of Metrology Tools

Assume the main process is up and in the "In Control" state for an exponential amount of time with the mean of mean time between failures (MTBF) of the process. The process goes to the "out-of-control" state and stays in this state until detected by the metrology tool. The quality of information extracted from the metrology measurements can be partly characterized by parameters α and β. The type I error, α, is the probability of rejecting a good product or process. The type II error, β, on the other hand, shows the probability of accepting a bad product or process. The power of metrology, $1-\beta$, is the probability of correctly rejecting a process or product. Accuracy, precision, and sampling policy in metrology are among the factors that affect the quality of information extracted from the metrology tool.

The time that is spent in the out-of-control state by the equipment is proportional to two factors; first, the time required for the results of the metrology tool to become ready, and second, the power of the metrology measurement. It is assumed that the equipment stays in the out-of-control state for an exponential amount of time with the mean of ACTM/$(1-\beta)$, where $(1-\beta)$ is the power of the metrology tool and ACTM is the average cycle time to metrology. ACTM is the response time from the metrology tool, which depends on the amount of WIP between the process and the metrology tool. After the metrology tool gives the signal that the process is out of control, the process is shutdown and the repair starts.

It is assumed that the tool stays in this state, which is called the "Failure Signal/Repair" state, for an exponential amount of time with the mean of the mean time to repair (MTTR). Because of the metrology type I error (α), there is a probability that the metrology tool generates a failure signal even though the process is in the good (in control) state. During any time interval h, in which the process is actually in the good state, the rate at which the equipment will be declared to be in the "Failure Signal/Repair" state is $(\alpha * h)$.

The above system is a description of a continuous-time Markov chain consisting of three states: namely, "In Control,"

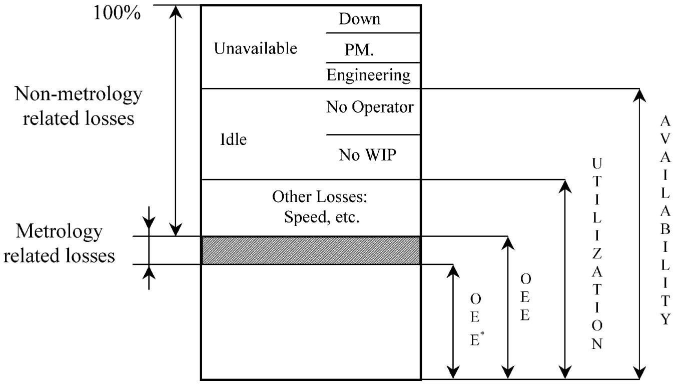

Fig. 2. The concept of OEE.

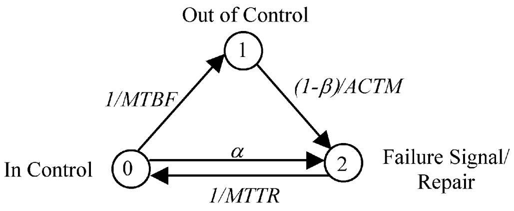

Fig. 3. Continuous-time Markov chain model of a metrology system.

Solving the limiting probability equations of this system [6] result in:

$$P_0 = \frac{1}{1+\frac{\text{ACTM}}{\text{MTBF}(1-\beta)}+\text{MTTR}\left(\alpha+\frac{1}{\text{MTBF}}\right)} \quad (1)$$

$$P_1 = \frac{\text{ACTM}}{\text{MTBF}(1-\beta)\left[1+\frac{\text{ACTM}}{\text{MTBF}(1-\beta)}+\text{MTTR}\left(\alpha+\frac{1}{\text{MTBF}}\right)\right]} \quad (2)$$

where P_0 and P_1 are the long-term probabilities of the process being "in control" and "out of control," respectively.

The process under control produces acceptable products, while the out-of-control process produces bad products that must be reworked. The faster the out-of-control state is detected, the faster the process is calibrated; which limits the amount of required rework. Therefore, the cost of a bad metrology practice is twofold. First, there is the cost due to the lost time of equipment (metrology and litho track), including the expenses of investment in purchasing and installing the machines, maintenance, footprint, etc. The second cost element occurs because of WIP rework, resulting in material, energy and labor costs. These costs are further studied in this section.

C. Revenue Models

Let N_i denote the number of machines of type i that are installed in the factory. Ignoring the requirement that N_i must be an integer, Leachman *et al.* [7] have shown

$$\left(\frac{D}{Y_F}\right) ThPT_i = N_i(\text{OEE}_i^*)(720) \quad (3)$$

to process $w = D/Y_F$ wafers per month; D is the designed output capacity and Y_F is the mature die yield. $ThPT_i$ is the total theoretical process time per wafer (expressed in hours) on equipment type i, considering all process steps performed by that equipment. The right-hand side is the total machine hours that can be devoted to processing (at theoretical rates) considering the achieved equipment efficiency. Assuming a revenue of R_0 for each wafer for the current day, the total revenue per day in the near future can be calculated as

$$\frac{R_0(N_i)\,(\mathrm{OEE}_i^*)\,(24)}{ThPT_i}. \tag{4}$$

Replacing the OEE* with ($P_0 * \mathrm{OEE}$), where the P_0 is the long run probability of the process being in the good (in-control) state, result in

$$\text{Revenue/Day} = \left[\frac{R_0(N_i)(\mathrm{OEE}_i)(24)}{ThPT_i}\right] \cdot \left[\frac{1}{1+\frac{\mathrm{ACTM}}{\mathrm{MTBF}(1-\beta)}+\mathrm{MTTR}\left(\alpha+\frac{1}{\mathrm{MTBF}}\right)}\right]. \tag{5}$$

As expected, the revenue increases with the decline of α, β, ACTM and MTTR and decreases with the decline of MTBF.

Over the long run, where the price is declining according to a continuous discount factor of γ, the total revenue realized up to time H (expressed in days), assuming zero start-up and production delays, is expressed as

$$\int_0^H \frac{R_0(N_i)\,(\mathrm{OEE}_i^*)\,(24)}{ThPT_i}\,e^{-\gamma t}\,dt = \frac{R_0(N_i)\,(\mathrm{OEE}_i^*)\,(24)}{ThPT_i}\left(\frac{1-e^{-\gamma H}}{\gamma}\right). \tag{6}$$

D. *The Effect of Metrology Tools on Ramp-Up*

Up to this point, the behavior of metrology tools was considered for mature and stable process technology. However, as depicted in Fig. 4, each process goes through three different phases: development phase where the process is first introduced, the ramp phase where the volume of production is increased, and the mature phase where the process sustains high volume production.

During the development phase, the equipment is installed and an appropriate recipe is applied. In this phase, the process usually does not produce any marketable product. Therefore, this phase is not in our interest. The process starts producing salable products in the ramp phase. In the beginning of this phase, equipment fails more often. After some time, the process is calibrated, the rate of failures declines, and the process becomes mature.

Here, we are interested in studying the effect of the metrology tools on the ramp phase. For simplicity, we approximate the above curve with a step function, where the process has the average ($\mathrm{MTBF}_{\mathrm{low}}$) in the development and ramp phases and jumps to the mature phase ($\mathrm{MTBF}_{\mathrm{high}}$) at time T (Fig. 5).

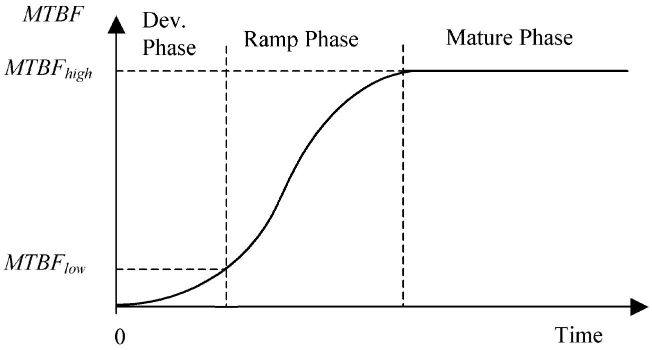

Fig. 4. Different phases of a process life cycle.

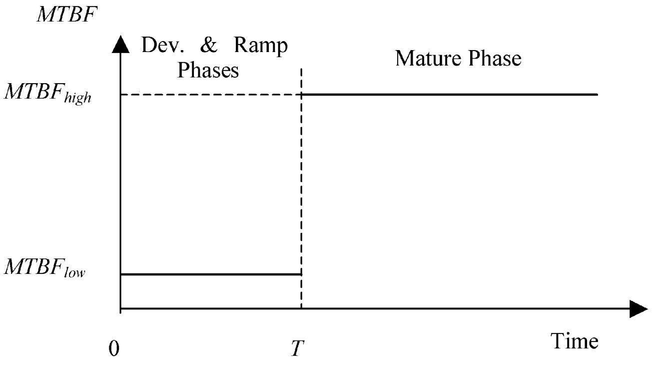

Fig. 5. A simplified process life cycle.

There are many factors affecting the duration of the ramp phase (T). Studying the behavior of these factors is beyond the scope of this paper. However, it is known that the ramp-up duration of the experience and knowledge comes from trial and error. Each equipment failure contributes to the knowledge about that equipment/recipe. Here, we assume the time to maturity is a function of the number of detected problems through time. The more problems are found, the more experienced the staff will become. Finally, after k number of trial and errors, the equipment goes to the mature state and the failure rate decreases. We are interested in finding the effect of metrology tools and the control policies on the value of T. Changes of T can then be translated to cost.

The number of required equipment is usually planned for the mature case; therefore, there is some lost revenue due to the unsatisfied demand in the development and ramp phases. Similar to (3), the satisfied demand in development and ramp phase (D_R), assuming the mature die yield, follows

$$\left(\frac{D_R}{Y_F}\right) ThPT_i = (N_i)(\mathrm{OEE}_i)(P_{0R})(720). \tag{7}$$

Here, the P_{0R} is the long-term probability of the process being under control during the development and ramp phases and follows an equation similar to (1). All of the notation in this section concerns the equipment performance in the development and ramp-up phases and is similar to the notation for the mature phase. Using (3) and (7), the unsatisfied demand per month during the development and ramp phases can be calculated as

$$D\left(1-\frac{P_{0R}}{P_0}\right). \tag{8}$$

Considering the continuous-time Markov chain model for the development and ramp phases, therefore, the expected value of T, the elapsed time for k number of repairs, can be calculated as

$$T = (k)(\text{ACTM})/[P_{1R}(1-\beta)]. \tag{9}$$

The total possible revenue during the development and ramp phases, assuming all demands are satisfied, can be expressed as

$$\int_0^T R_0 e^{-\gamma t}\frac{D}{30}\,dt. \tag{10}$$

Here, γ is the continuous discount factor for the exponentially declining sales price. The lost revenue can be calculated as

$$\int_0^T R_0 e^{-\gamma t}\frac{D}{30}\left(1-\frac{P_{0R}}{P_0}\right)dt. \tag{11}$$

The total lost revenue can be calculated as

$$\Delta R = R_0\left(\frac{D}{30}\right)\left(1-\frac{P_{0R}}{P_0}\right)\left(\frac{1-e^{-\gamma(k.\text{ACTM}/P_{1R}(1-\beta))}}{\gamma}\right). \tag{12}$$

E. Comprehensive Revenue Model

The comprehensive revenue model consists of the combined revenue obtained in the ramp phase and the mature phase. The total revenue obtained in the ramp phase can be expressed as

$$R_0\left(\frac{D}{30}\right)\left(\frac{P_{0R}}{P_0}\right)\left(\frac{1-e^{-\gamma(k.\text{ACTM}/[P_{1R}(1-\beta)])}}{\gamma}\right). \tag{13}$$

Given the duration of the mature phase, the total revenue obtained in the mature phase can be calculated by (6). The summation of (6) and (13) should be considered in selecting the metrology setup.

The revenue models are more tailored toward the marketing department's needs versus the manufacturing expenses. In other words, they only consider the incoming cash flow to the company through sales. These models do not consider the outgoing cash flow and the expenses of the company. What if a metrology tool improves revenue, but the price of investment is high? How about the maintenance expenses and labor costs associated with each metrology system? These issues will be addressed by another model, called the cost model, in the following section.

F. The Cost Model of Metrology Methods

Leachman *et al.* [7] expressed the annual expense of a fab as

$$\sum_i \underbrace{(Ce_i+Le_i+Se_i)}_{CM_i} N_i + \underbrace{(Lw+Mw+Sw)}_{CW}.12.w + (Lf+Sf). \tag{14}$$

The first term captures the machine expenses. Ce_i, Le_i, and Se_i are the amortized annual costs due to purchasing, labor, and foot-prints, respectively, per machine of equipment type i. CM_i captures the total amortized annual cost per machine of equipment the amortized annual cost due to labor, material, and infrastructure per wafer started. CW is the total amortized annual cost per wafer started. The last term captures the annual fixed cost of manufacturing. Lf and Sf are the fixed labor cost and the fixed space cost, respectively, that are independent of wafer start volume and the number of installed equipment.

Using (1), (3) and (14), the total expenses of the machines per year can then be expressed as

$$\begin{aligned}&\text{EPY(Machines)}\\ &= (CM_{\text{litho}})(D)(ThPT_{\text{litho}})\\ &\quad\cdot\left[\frac{1+\frac{\text{ACTM}}{\text{MTBF}(1-\beta)}+\text{MTTR}\left(\alpha+\frac{1}{\text{MTBF}}\right)}{720(Y_F)(\text{OEE}_{\text{litho}})}\right]\\ &\quad+(CM_{\text{met}})(N_{\text{met}})+\sum_{i\in\text{other}}(CM_i)\frac{(D)(ThPT_i)}{(Y_F)(\text{OEE}_i)(720)}.\end{aligned} \tag{15}$$

The "litho" subscript represents the lithography system, which includes the exposure unit and the track line. The first term in (15) captures the effect of metrology in lithography costs through its effective processing time. The second term is the cost associated with the purchase, maintenance and the footprint of metrology devices. The third term captures all other equipment expenses in the fab.

As discussed earlier, different metrology methods generate different amounts of WIP and rework. The rework consumes materials, energy and labor. Furthermore, the mask life, which is considered dependent on the number of exposures, causes the expenses to increase in proportion to the amount of rework. According to our continuous-time Markov chain model, the total out-of-control machine-hours spent processing w_{rl}, the number of wafers in lithography to be reworked, will be:

$$(w_{rl})(ThPT_i) = \left(\frac{P_1}{P_0}\right)(N_i)\left(\text{OEE}_i^*\right)(720). \tag{16}$$

Considering (1)–(3), and (16), the total number of reworked wafers in lithography per month can be calculated based on the total monthly production rate as

$$w_{rl} = \left[\frac{\text{ACTM}}{(1-\beta)\text{MTBF}}\right]\left(\frac{D}{Y_F}\right). \tag{17}$$

The fab total expense per year due to the number of wafers started includes two terms. The first term captures the expenses due to the reworked wafers in lithography steps. These expenses reflect material costs, energy, labor and masks. The second term includes all expenses that are functions of the number of wafers started. All the rework done on the other equipment sets (except lithography) are assumed to belong to this category. Therefore, the total expenses per year due to the number of wafer starts is

$$\begin{aligned}\text{EPY(Wafer started)} &= (CW_{rl})(12)\left(\frac{D}{Y_F}\right)\\ &\quad\cdot\left(\frac{\text{ACTM}}{\text{MTBF}(1-\beta)}\right)+(CW_{\text{other}})(12)w.\end{aligned} \tag{18}$$

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